PRD-66 Hot Gas Filter Development

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Introduction

The PRD-66 manufacturing process offers a unique approach to the production of hot gas candle filters for application in Pressurized Fluidized Bed Combustors (PFBC) and Integrated Gas Combined Cycle (IGCC) power generation systems. Fabricated from readily available and inexpensive raw materials, the PRD-66 process uses an admixture of textile and ceramic concepts to produce an all-oxide filter element comprised of alumina, cordierite and mullite. Although it has an “apparently” fibrous structure, PRD-66 products contain no refractory ceramic fiber (RCF) residues in the finished products. The use of textile grade glass yarn as a consumable reactant gives the advantages of fabrication versatility and shape control and a unique micro-layered phase structure in the fired product, resulting in unsurpassed thermal shock resistance and operating temperature capability of greater than 1200°C in a low-cost package. This high throughput, adaptable process allows tailoring of filter element dimensions and operating properties to specific system needs with short lead times and low cost penalties.

Despite early successes, the original PRD-66 elements experienced significant damage during the final phase of testing at AEP’s TIDD PFBC facility, in 1995. Filters produced by this process appeared to lack absolute filter membrane integrity and showed indications of a failure mode believed to result from infiltration of ash particles into the filter body. Under this contract, process and product modifications were developed which dramatically improved both the permeability and the surface filtration characteristics of the PRD-66 filter elements. The enhanced filters, which were subsequently produced, were made available for a variety of exposure trials including Westinghouse’s high temperature, high pressure testing (a PFBC simulation), Foster Wheeler’s pressurized circulating fluidized bed combustion (PCFBC) facility in Karhula, Finland, and Southern Company Services’ Power Systems Development Facility (PSDF) in Wilsonville, AL. Concurrently, the reproducibility and scaleability of modifications was demonstrated.

Objectives

1. Develop testing equipment and methodology for assessment of membrane integrity and filtration efficiency of PRD-66 candle filters.
2. Develop new membrane application technology to supplement or replace the 'wound-on' membrane of the original demonstration filters.
3. Conduct an extended process capability demonstration to assess controllability and product uniformity.
4. Evaluate filters that were exposed to actual PFBC conditions.

Approach

In order to determine the leakage mode which contributed to observed infiltration failures during TIDD-5, lab-scale equipment and techniques were developed to simulate in-use exposure to coal ash which used short filter segments at room temperature. Based upon the results of this evaluation, an enhanced performance membrane and application process were developed. Research focused on modifications to methods and materials which were either consistent with the basic PRD-66 technology or reasonable extensions of it.

Once the preferred filter configurations were devised, both a “Process Capability Demonstration” and a “Manufacturing Demonstration Run” were conducted which incorporated the new technology. Filters produced during the course of these demonstrations were submitted to various testing programs for evaluation. Analysis of the test results focused on determining if the improved material functioned as a surface filter, and establishing whether or not the material was chemically and physically stable during actual field exposures.

Results

Assessing Membrane Integrity and Filtration Efficiency

In order to rapidly evaluate the filtration efficiency of the PRD-66 filter membrane, a particle infiltration tester (PIT) was designed and fabricated, as shown in Figure 1.

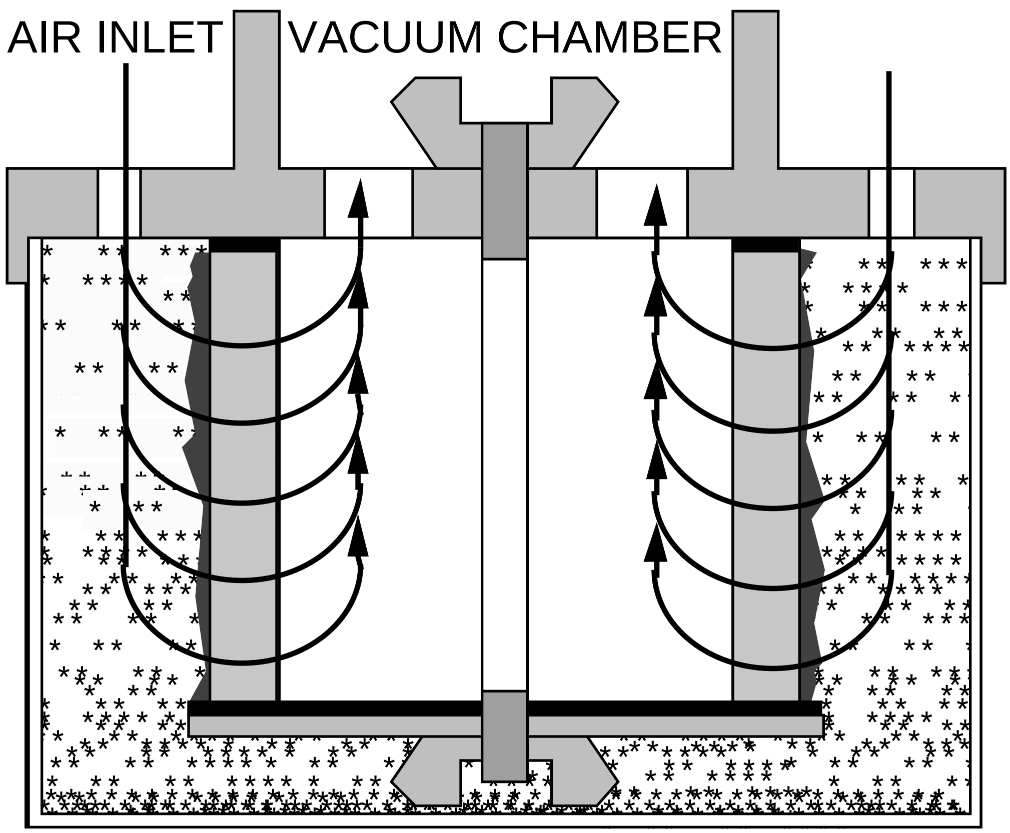

Figure 1: Particle Infiltration Tester (PIT)

Short segments (5-8 cm long) were cut from complete filters and mounted in this apparatus. A small amount of representative coal ash, from the TIDD reactor test, was placed in the chamber and deposited onto the exterior surface of the specimen by applying a brief vacuum induced air flow while agitating the dust. The ash layer was then removed by brushing; the process was repeated as many cycles as desired. A typical test included exposure to 25 cycles of ash impingement. Samples were then removed for examination.

The assessment of the membrane's surface filtration capability relied on the fact that the PRD-66 material is highly translucent in nature. When lit from within, the surface of the as-manufactured material has a very bright "light amber" glow; Figure 2 depicts the appearance (as best as possible in black-and-white). If the membrane is inadequate, it allows ash to become entrained in the filter wall, beneath the membrane. Because coal ash (such as that taken from TIDD) contains significant concentrations of iron, it has high opacity and excellent hiding power. As a result, areas where ash penetrates into the body of the filter show up as dark blotches when illuminated from within, as shown in Figure 3.

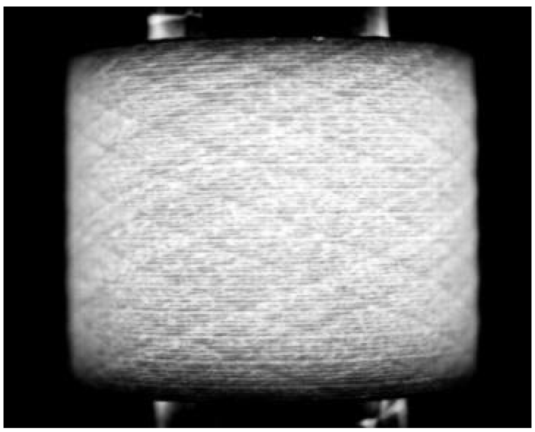

Figure 2: As-manufactured filter as viewed in under transmitted light.

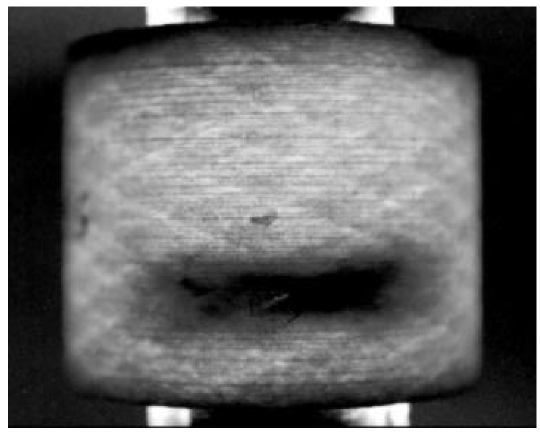

Figure 3: After 25 PIT cycles, areas of ash penetration occlude light

These two factors, when taken together, suggested an evaluation of PIT-exposed specimens based on the use of transmitted light to determine the extent and location of ash infiltration through the membrane. Figure 4 shows an example of a PIT-exposed segment made with the 'wound-on' membrane of the initial demonstration filters viewed with transmitted light. When compared to an untested filter segment (Figure 2), areas of ash infiltration appear as dark streaks and spots; in the case of the original membrane, these areas are many and widespread.

Closer examination of the filter segment shown in Figure 4 and similar samples indicated that the infiltration had occurred in areas between the adjacent yarns of the 'wound-on' membrane. Apparently, the alumina slurry coating on the fiberglass yarns on the surface of the filter did not consistently bridge the gaps between the yarns and an incomplete membrane had formed. Figure 5 depicts the cross-section of a filter made with the original "wound-on" membrane.

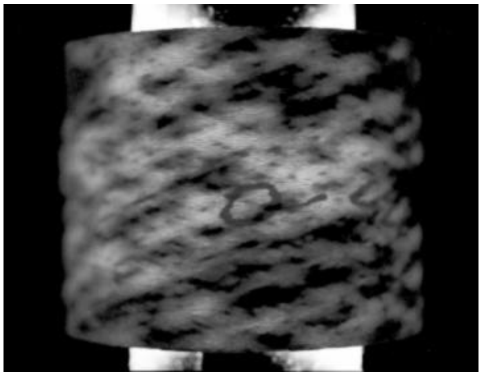

Figure 4: Original filter after 25 PIT cycles, viewed in transmitted light

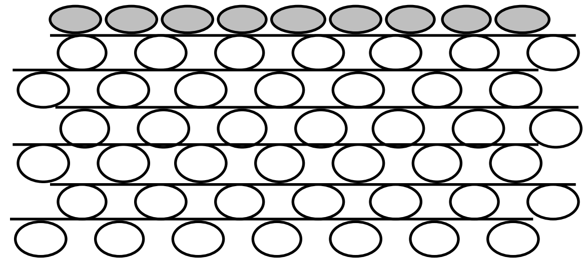

Figure 5: Wall cross-section with original wound membrane

Membrane improvement

After studying the membrane integrity in this fashion, improvement efforts were focused on the addition of membrane material between the as-wound yarns to enhance the filtration performance. To facilitate this addition, a new pattern was chosen for the membrane yarn allowing broader spacing between adjacent yarns. Instead of relying on the microcracks in the alumina slurry to provide adequate filtration, a more controlled material would be used to fill in the gaps and provide a more uniform porosity. Figure 6 depicts the cross-section of the filter wall showing the additional filler material between the 'wound-on' surface yarns, and the additional membrane area incorporated in this process. The compositions of the slurry coating of the membrane yarn and the filler materials were varied over as wide a range of options, and representative samples were subjected to 25 PIT-exposure cycles. Candidate membranes were selected for further evaluation if they consistently produced filter specimens with no ash penetration, as shown in Figure 7.

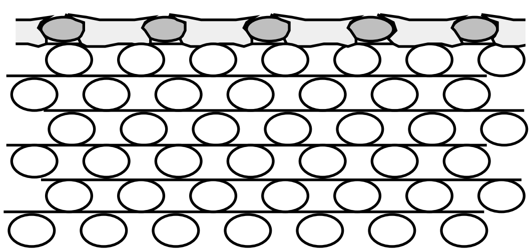

Figure 6: Wall cross-section with wound membrane plus membrane filler

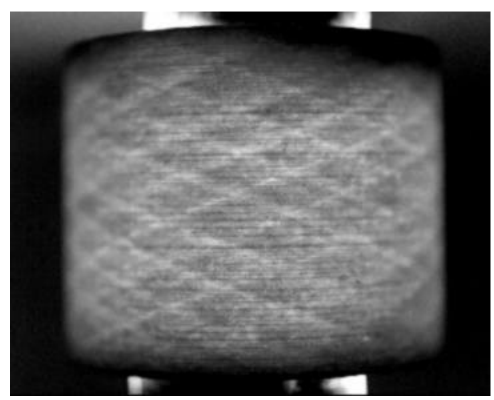

Figure 7: Improved membrane after 25 PIT cycles shows NO ash penetration

From the many candidates, two variants were selected for further evaluation. These membrane versions, PRD-66M and PRD-66C, were selected for their excellent but different combinations of filtration performance and flow resistance characteristics. PRD-66M, has a mean pore size of about 10.5µ (Figure 8) with flow resistance comparable to the close wound membrane filters. PRD-66C was chosen because only half the flow resistance, but still exhibited excellent filtration performance, having a mean pore size of about 25µ (Figure 9).

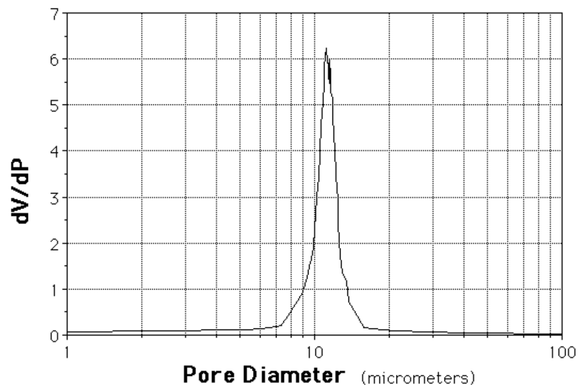

Figure 8: Pore Size Distribution of PRD-66M

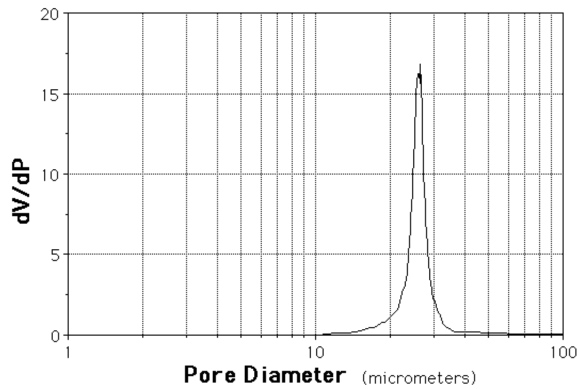

Figure 9: Pore Size Distribution of PRD-66C

Figure 10 compares the resistance-to-flow of filters fabricated with the PRD-66C and PRD-66M membranes. Both types of filters have values well within the specification required by Westinghouse for use in their Advanced Particle Filtration System.

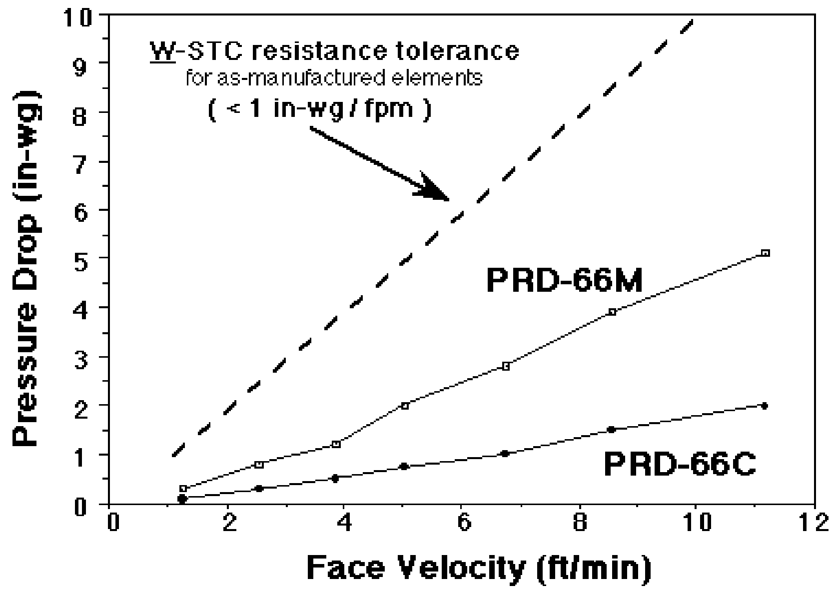

Figure 10: Flow resistance of PRD-66M and PRD-66C

Process Capability and Manufacturing Demonstration Runs

Extended process capability demonstration and manufacturing demonstration runs were completed which assessed controllability and product uniformity. A total of eighty filters were fabricated, most having the Type-C membrane; filters were generally produced in batches of ten. In between each batch, engineering evaluations were performed to determine if improvements could be made before the next batch was produced. Most changes only impacted the processability and had no impact on compositions or dimensions. The exception was a modification to the design of the mandrel on which filters are wound. This redesign allowed for the use of more readily available materials for constructing the mandrels, and allowed for easier removal of the filter tubes. This modification altered the shape of the filter's closed end from "spherical with a blunt protrusion" to a gradual taper; it also resulted in a slightly smaller inside diameter (45 mm versus 46 mm).

Field Testing

The filters, which had been produced during the process capability and manufacturing demonstration runs, were made available to FETC-supported test programs as the opportunities arose. Those field tests included:

- **Westinghouse-STC High Temperature High Pressure (HTHP), Pittsburgh, PA**

Date	April/May 1997
Filter Operating Temperature, deg.C	843
Time, hrs	120
Accelerated Pulse Cycles	2200
Thermal Excursions	12
Number of Startup/Shutdown Cycles	7

- **Westinghouse-STC Advance Particulate Filtration System with Foster Wheeler PCFBC, Karhula, Finland**

Date	September 4, 1997 – November 7, 1997
Number of Filter Elements Tested	8
Filter Operating Temperature, deg.C	700 - 750
Filter Operating Pressure, bar	9.5 - 11
Coal Feed	Eastern Kentucky
Sorbent	Florida Limestone
Time, hrs	581 (6)*, 342 (1), 239 (1)
Face Velocity, cm/sec	2.8 - 4.0
Particle Load, ppmw	6000 - 9000
Particle Size, microns	< 1 - 150
Thermal Excursions	None
Number of Startup/Shutdown Cycles	7

* The number in parentheses indicates the number of elements exposed for the respective operating hours

- **Westinghouse-STC Advance Particulate Filtration System with MW Kellogg Transport Reactor at Southern Company Services PSDF, Wilsonville, AL**

Testing began in early June 1998 and is still in progress, with twelve PRD-66C filters in service.

Summary of Exposure Results

Both PRD-66C and PRD-66M were evaluated in Westinghouse's HTHP and passed all of their requirements, but only one filter type could be selected for exposure in Finland. PRD-66C was chosen as the candidate for further qualification for PFBC applications, primarily because of its lower flow resistance and good filtration efficiency with PFBC ash (as determined by the PIT-test).

After 120 hours of exposure to HTHP conditions and 581 hours of exposure to PFBC conditions in Karhula, the integrity and filtration characteristics of the filters were evaluated. Throughout the testing, there were no in-process failure, no delaminations, no "divots", and no cracks. The microstructures were examined by scanning electron microscopy (SEM) and x-ray diffraction (XRD) and no morphological changes had occurred. "Fast-fracture" samples were prepared from the Karhula-tested PRD-66C filters to expose a cross-section of the wall. The contrast between the "orange-brown" ash and the "white" filter material made it easy to determine where obvious ash penetration may have occurred. The most significant observation was that there was no ash just below the membrane. This indicated that the new PRD-66C membrane (with nominal 25-micron pores) is an effective surface filter for PCFBC applications. To confirm this, FW supplied enough the Karhula PCFBC ash to conduct a particle infiltration test (PIT) on a "sister" candle filter; no penetration of ash through the membrane was detected.

In addition, several exposed filter elements and several as-manufactured elements were tested to determine if any strength deterioration had occurred; the results are depicted in Figure 11. DuPont Lanxide Composites (DLC) conducted o-ring diametrical compression tests on 1"-wide specimens, Westinghouse Science and Technology Center (W-STC) conducted c-ring compression tests on 3/4"-wide specimens. Each bar on the graph represents the range of data for a particular element, "n" is the number of rings tested. The filter element identification number is indicated below each bar; the letter "C" indicates a PRD-66C membrane, "M" indicates a PRD-66M membrane. The filters were produced over a 2-3 month period and all numbers were assigned chronologically. Lightly shaded bars indicate that the filter was not exposed to the test environment; dark bars were used for the field-exposed elements. It was interesting to note how well DLC's o-ring data agreed with W-STC's c-ring data for filters M570 and C573, which were tested in both labs. It seemed reasonable, therefore, to evaluate all available test data together.

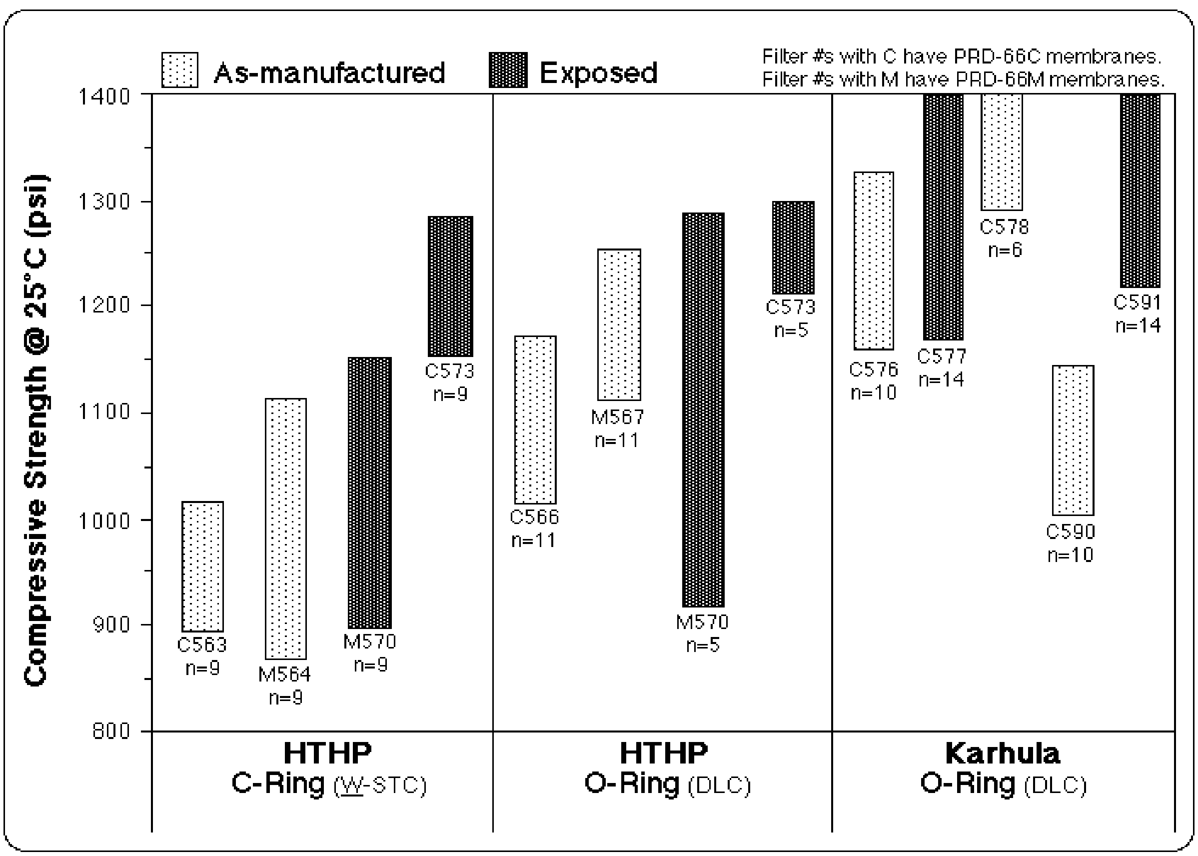

Figure 11: Comparison of PRD-66 strength data suggests that strength was unaffected by these exposures when compared to general population of unexposed elements

After reviewing this data, no apparent difference seemed to exist between the compressive strength of the as-manufactured material and the filters exposed to actual, and simulated, PFBC conditions. It remains to be seen if this stability is maintained over longer exposure periods. It did, however, appear that candle filters made later in time were stronger than those fabricated earlier; during the course of the "demonstration runs" process controls were gradually improved.

Three of the filters field-tested in Karhula were forwarded to Southern Company Services' Power System Development Facility (PSDF) in Birmingham, Alabama. Along with six new PRD-66C elements, they were installed in a Westinghouse Advanced Particulate Filtration System, downstream of an MW Kellogg transport reactor, operating in "combustion mode". During the start-up of the run, an event occurred that caused a sudden 300°C temperature increase on the surface of the filter elements; shortly afterward, significant damage to the monolithic oxide elements was suspected. The cluster of elements was cooled and removed from the filtration vessel. According to PSDF engineers, none of the PRD-66C filters showed any indication of damage! The system was started back up again and accumulated over 550 hours of operation before it was shut down, as planned. All PRD-66C candle filters looked good and three more filters were put in service. The system was put back on-line to accumulate an additional 1,000 hours.

Future Activities

All of the technical objectives of the original contract have been achieved. As a result of the process capability run, the manufacturing demonstration run, and the field testing, several issues have come to light which will be addressed in two new tasks which have been added to this contract. One task will focus on equipment related issues, the other involves developing a membrane on the inside diameter of the filter element.

Acknowledgments

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Contract Information

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